



Spectral classification of stars

Study time: 3 hours

Summary

In this activity you will learn how to classify main sequence stars according to their spectra. The activity is based around a software package that allows you to view and compare stellar spectra. You will measure the wavelengths and intensities of absorption lines and study how the prominence of certain lines varies across spectral classes.

The software package also includes a simulation of an astronomical telescope and you will use this to obtain spectra of some of the stars in the Pleiades. The analysis of these data will allow you to measure the distance to this star cluster.

Before doing this activity you should have read as far as the end of Chapter 3 of *An Introduction to the Sun and Stars*.

The activity is based on a software package called the Virtual Educational Observatory (VIREO) developed by a group called Contemporary Laboratory Experiences in Astronomy (CLEA) that is based at Gettysburg College, Pennsylvania, USA.

Learning outcomes

- With reference to a spectral atlas, the ability to classify main sequence stars according to the Harvard Spectral Classification scheme.
- Better understanding of the technique of spectroscopic parallax, including the ability to determine the distance to a star using this method.
- An appreciation of the factors that are important in making efficient use of telescope time.

Background to the activity

The Harvard Spectral Classification scheme (O, B, A, F, G, K, M) (*An Introduction to the Sun and Stars*, Section 3.3.2) is based on correlating absorption line strengths with photospheric temperature. Since absorption lines might be considered to be fine detail in the spectrum, you will appreciate that you will need to pay quite close attention to the spectra.

The astronomers who developed the Harvard system, Annie Jump Cannon and E.C. Pickering, classified an astonishing 225 300 stars in their original 'Henry Draper Catalogue'. This was published from 1918 to 1924. You will be studying some 'unknown' spectra that relate to stars in this original catalogue, which are identified by the letters 'HD'.

In this activity we will consider only the spectra of main sequence stars. It is important to note, however, that the software package contains spectra of stars that are not on the main sequence, and that the classification of spectra is given

by an extended scheme called the MK system. The MK system describes spectral classes in the same way as the Harvard scheme, but includes an indication of the stars' luminosity. The luminosity is indicated by a roman numeral (I, II, III, IV or V) called the luminosity class, with I as the highest and V as the lowest (see *An Introduction to the Sun and Stars*, Section 4.4.2). Main sequence stars are all of luminosity class V, and in this activity you will only need to consider spectra that have this luminosity class (e.g. G0 V, K5 V, M5 V, etc.).

Another convention that you need to be aware of when carrying out this activity is that all wavelengths are measured in units of 10^{-10} m. This unit is called the ångström, and has the symbol Å. The ångström is commonly used in astronomy, although you may not have come across it before, since in this course we express wavelengths in the visible part of the spectrum in units of nanometres (nm).

- How many ångströms are there in a nanometre?
- 10. Since a nanometre is 10^{-9} m, and one ångström is 10^{-10} m, there are $10^{-9}/10^{-10} = 10$ ångströms in one nanometre.

This activity requires several windows to be open at once, and is easier to use if you have your computer set to a high screen resolution. If you know how to change the screen resolution of your computer you may want to do that before starting the activity, but it is not essential that you do so.

This is a fairly long activity so it has been divided into parts. The estimated study times are given for the individual parts.

Setting up the VIREO software package

- If you have not already installed the VIREO package, start the S282 Multimedia guide and then click on The spectral classification of stars in the 'Stars' folder. Follow the instructions to install VIREO. This may take several minutes to load.

VIREO includes a range of default options which include a simulation of the process of applying for telescope time to access large telescopes before observing. Time is not always "awarded" so it is useful to turn off this option the first time you use VIREO. To do this:

- start VIREO using the shortcut on your desktop. The opening screen of the CLEA package will be displayed.
- Click on its menu item File | Log In...A new window called Student Accounting will open.
- Type Instructor (not case sensitive) in the box labeled Student #1 and click OK. Answer YES to the question Have you finished logging in? A small dialog box will appear, asking for a password. The default password is CLEA (case sensitive). Enter it in the box and press OK. A window called Optical Simulation Options will open with the General tab selected.
- Click on the box labelled Restrict Scope Access to remove the tick. Click OK and click YES in the dialog window that follow.
- Exit VIREO using the File | Exit Observatory menu item.

The spectral classification of main sequence stars

Part 1 Familiarization with the display of stellar spectra

This part of the activity should take about 15 minutes.

- Start VIREO using the shortcut on your desktop.
- The opening screen of the CLEA package will be displayed. Click on its menu item File | Log In...
- A new window called Student Accounting will open. You should enter your in the box labeled Student #1. The software uses your name as a way of naming folders for containing the results that you obtain. The software was originally written for teaching in undergraduate teaching laboratories – hence the option to login as a group of students at a particular table. You only need to fill in your name, press OK and then confirm that you have finished logging in.

You will now see the main title screen for the Virtual Educational Observatory (VIREO). It is from this screen that you can choose a number of different activities. Here we will be using the Classification of Stellar Spectra exercise.

In this part of the activity we will be interested in using the spectral classification tool.

- Select the menu item File | Run exercise | “Classification of Stellar Spectra”. This opens a new window entitled The Classification of Stellar Spectra. Select the menu item Tools | Spectral Classification and take a moment to look at the layout of the new screen that is displayed (titled Classify Spectra). You should see that the horizontal axis has a scale from 3700 to 4700 ångströms – this is the wavelength scale for displayed spectra. Change this range to 3900 to 4500 ångströms for this activity by selecting the menu item File | Display | Spectral range...and set the minimum and maximum wavelengths to 3900 and 4500 ångströms using the slider, then click OK. This wavelength range is typical for stellar classification.
- What part of the spectrum does this wavelength range correspond to? Look back to *An Introduction to the Sun and Stars* Figure 1.36 and note the corresponding colour(s).
- The wavelength range extends across the violet part of the spectrum.

The vertical axis shows the spectral flux density from the star in arbitrary units. This axis is labelled ‘Normalized Intensity’. Note that the axis is without any numerical values – we will return to consider this in more detail when we display the first spectrum.

You should also note that the screen is split into three panels. Each of the three panels can be used to display a spectrum. The central panel will hold the unknown spectrum that we wish to classify, and the panels above and below it can be used to display known reference spectra. This layout, with an unknown spectrum between two known spectra allows comparisons to be made between spectra, and greatly helps in the classification process.

The software package contains 25 ‘unknown’ stellar spectra. Later in this activity you will classify all of these spectra in turn, but to start with, we will describe in detail how to go about classifying the first two stars from this list.

- To load the first spectrum for study select the menu item File | Unknown Spectra | Program List. This opens another window with a list of stars.
- Select the first star in the list – HD 124320 – and double-click to open the spectrum. Notice that the spectrum of HD 124320 now appears in the central panel of the classification window.
- The spectrum is shown as a graph of ‘Normalized Intensity’ against wavelength. In this software package, normalized intensity means that the highest intensity is given the numerical value of 1.00 and that all other intensities are scaled accordingly.
- Click on the highest point of the curve to confirm this. The intensity value will be shown at the bottom of the window. Note also that when you click on the spectrum to make a measurement, the wavelength is also displayed at the bottom of the screen. Click on the horizontal axis to check that it represents zero intensity.

The spectrum appears as a ‘plateau’ of slowly varying high intensity into which cut four or five deep notches. The notches are absorption lines and the ‘plateau’ part is the continuum. In our study of spectral classification we will be interested in both of these components.

- Note that you can also view the spectrum in a ‘photographic’ form by using the menu: File | Display | Grayscale “Photo”. This reveals the absorption lines as narrow dark bands.
- Switch back to the graphical display File | Display | Intensity Trace.
- Click on the lowest point of each of the three deepest absorption lines. Record their wavelengths and normalized intensities. Your results should be close to wavelengths 3970, 4102, 4342 Å and normalized intensities 0.27, 0.29, and 0.27 respectively.

Question 1

For the spectrum that is currently displayed:

- Determine the normalized intensities at 4050 and 4400 Å.
 - Roughly estimate the wavelength at which the continuum seems to have its maximum value.
 - Decide if the star will appear red or blue.
 - Surmise if this star has a hot or cool photosphere (say, in comparison to that of the Sun).
-

Although we have examined this spectrum and concluded that the star probably has a higher photospheric temperature than that of the Sun, we cannot assign a spectral class to the star unless we compare it to some known ‘standard’ spectra. In the next part of the activity you will classify this spectrum and those of the other unknown stars that are given in the Program List.

Part 2 The classification of stellar spectra

This part of the activity should take about 45 minutes.

This part of the activity is a study of the distinguishing characteristics of the spectra of main sequence stars. You will compare some unclassified stellar spectra with reference spectra to enable you to determine the correct spectral classifications. You will start by attempting to classify the spectrum of HD 124320, so ensure that you have this spectrum displayed (look back to Part 1 to see how to do this if you have taken a break from the activity).

- Click on the menu item File | Atlas of Standard Spectra.
- In the new window select Main Sequence by double-clicking.

Reference spectra from the main sequence catalogue will now be shown in the panel labelled “Standards” on the right-hand side of the window. The spectral classifications shown include the Roman numeral ‘V’, indicating the luminosity class in the MK classification scheme. Since this activity is based only on main sequence stars you may omit the ‘V’ when writing down any classifications that you arrive at.

- You can scroll through this catalogue using the scroll bar. Astronomers often refer to spectral classes as ‘early’ or ‘late’. The early classes (O, B, A) are at the top of this catalogue and the late classes (K, M) at the bottom. Click on a reference spectrum to display it in the top panel, above the unknown spectrum. The next spectrum in the atlas will be displayed in the bottom panel. Notice how the overall continuum shape changes through the spectral sequence.

In light of what you’ve observed so far consider the following points.

- What does the varying shape of the continuum indicate?
- ☐ It is caused by the systematic change in photospheric temperature across the spectral classes.
- Use the location of the peak in the continuum to decide which star has the coolest photosphere and which has the hottest.
- ☐ The coolest photosphere is from class M5 and the hottest O5.

Although this is slightly ambiguous (the nearby spectra are very similar) you will have seen that the continuum peak for O5 is off the short wavelength end of the spectrum (in the ultraviolet) and M5 has its peak beyond the long wavelength end.

- Scroll through all the spectra in the Classification Atlas again, and compare the selection of spectra available with Table 3.2 of *An Introduction to the Sun and Stars*. Note any differences.
- ☐ The two sets are very similar and the only difference is in the range of the sequence. Both start with O5, the first in the spectral sequence. However, this Atlas only runs as far as M5 whilst Table 3.2 extends to M8.

As you scanned through the Atlas you probably noticed that the strength of spectral lines varies through the sequence. If not, look once again at the Atlas, before considering the following question.

Question 2

Why does the strength of a spectral line change with spectral type? (To answer this question fully, you may need to refer back to *An Introduction to the Sun and Stars*, Section 3.3.2.)

Return to the O5 spectrum and note the narrow dip about one-quarter of the way from the long wavelength end. This absorption line grows stronger in the later spectral classes shown lower down the window.

- Look at each spectrum in the atlas and decide in which spectral class this line is strongest.
- This line is strongest in the A1 class.
- Click on the lowest point of the same absorption line (one-quarter of the way from the long wavelength end) on the three displayed spectra and note the wavelengths in each case.
- You should obtain values of approximately 4340 Å in all three cases.

So it appears as though this is the same spectral line. At this point it is useful to identify the line, i.e. to determine what element or ion is responsible for absorption at this wavelength.

This spectral classification software includes a table of the most prominent spectral lines, and we will now use this table to identify the line at 4340 Å.

- Click on the menu item File | Spectral Line Table. Place the cursor on the coloured title bar of the new window, hold down the left mouse button and drag the table off the classification window so that both windows are visible.
- Either scroll down the Spectral Lines window to find the closest match to this line, or simply click on the lowest point of the line, in the classification window, to get the software to find the match.

With this in mind consider the following queries.

- Which line is the closest match to the feature at 4340 Å? What element does it arise from and what is the ionization state of this element?
- The line is described as H γ (H gamma). This is the H γ line of hydrogen, i.e. the third line in the Balmer series (see *An Introduction to the Sun and Stars*, Section 3.3.2). The H γ indicates it arises from un-ionized (or 'neutral') hydrogen.

You are now ready to attempt a classification for HD 124320. The general principle is to find the reference spectra that provide the closest match to the unknown spectrum. Often the unknown spectrum will have an appearance that lies between those of two reference spectra. If it appears 'mid-way' between two reference spectra then you can assign it to the spectral class that lies mid-way between the classes of these reference spectra. If it is closer to one reference than the other then you should assign it to a class that is closer to one reference class than the other.

Of course, there is a degree of subjectivity to such classification, but with practice you should be able to classify a main sequence stellar spectrum to within two-tenths of a spectral class.

To proceed with the classification click on each of the standard spectra in turn and compare with the spectrum of HD 124320.

- Which spectral types are the closest match to HD 124320?
- A1, A5 are both very similar to HD 124320. F0 is reasonably similar, but probably not as good a match as A1 or A5.

So, you would justifiably conclude that the classification of HD 124320 lies between A1 and A5. To investigate in more detail we can use another feature of

this software package – one which shows the difference between an unknown spectrum and a reference.

- Select the menu option File | Display | Show Difference. This subtracts the spectrum of HD 124320 point by point from the reference spectrum at the top of the window and displays the result at the bottom.

Question 3

Using the Show Difference function, now decide which spectral types are the closest match to HD 124320. If you had to attribute a spectral class (that might not be shown in the Atlas) to HD 124320, what would it be?

The difference plot is very close to zero except for one feature.

Question 4

Use the cursor to measure the wavelength and size of the discrepant feature identified in Question 3. Now use the menu item File | Spectral Line Table to identify the spectral line, and explain what the table entry means. Note that by double-clicking the mouse button on a table entry, you can obtain additional information about the line. What does the feature in the difference plot represent? Give as full a description of this line as you can.

- Record your classification of the spectrum of HD 124320 by clicking on the menu item Classification Results. A new window titled ‘Observational Data’ will open. Enter the class in the box labelled Sp. Type and the reasons for your choice in the box labelled Remarks and click OK. A message will appear to tell you the data have been added to the results list.

Note that all your results can be stored in this way – and this will be useful when you come to compare your spectral classifications with those given at the end of these notes. If you want to amend or print your table of results, use the menu item Tools | Results Editors | Observational Results | Display/Print/Save Text... which can be found on the main exercise window (you may need to move the Classify Spectra window to one side to access the main window). A new window entitled “Recorded Results” will appear. To print the results select List | Print. To amend an entry, double-click on it and select Edit from the pop-up menu.

Note that if you want to take a break from the activity, you must save the results in a file using the menu item Tools | Results Editors | Observational Results | Save Data... from the main exercise window. To reload data after a break go to Tools | Results Editors | Observational Results | Load Saved Data...

- Now inspect the CaII K line in more detail (see the answer to Question 4). Scroll through the reference spectra and note the behaviour of this line throughout the spectral sequence.

Question 5

Describe qualitatively how the CaII K line varies across the whole spectral sequence. Compare your findings against Figure 3.23 of Chapter 3 in *An Introduction to the Sun and Stars* (note that the term ‘ionized calcium’ in Figure 3.23 refers to the CaII K line).

This completes our work on HD 124320. Next you will use the software to classify the second unknown spectrum in the list, that of the star HD 37767.

- Go to the menu item File | Unknown Spectra | Next on List.

Question 6

- (a) Using a similar approach as you adopted for HD 124320, estimate the spectral class of HD 37767.
- (b) For the spectrum of HD 37767 list the wavelengths of all the spectral lines that you can find. Identify as many of these lines as you can.

You might find it useful switch to the grayscale or 'photo' display (File | Preferences | Display) to see the visual appearance of this line, and how the neighbouring reference spectra compare. You may also have difficulty identifying some lines because they overlap one another. You can use the Zoom feature to take a closer look, but you may not be able to unambiguously identify every line.

The final task in this part of the activity is to classify the remaining stars in the unidentified stars list. Although there are over 20 stars in the list you will find that the process of assigning stars to classes becomes much faster once you have had some practice. You should start with the stars HD 6111 and HD 5351 since the notes at the end of this activity describe in detail how the classes for these two stars are arrived at. Remember to record your results using the menu item Classification Results and, if you want to take a break, to save a file of your results using the menu item Tools | Results Editors | Observational Results | Save Data... from the main exercise window.

- Classify all of the unknown stars in the 'Unknown spectrum' list. You can obtain the list of stars by the menu item File | Unknown Spectrum | Program List.
- To select a particular star scroll down the pop-up window and double-click the star name. Then classify the star using the techniques that you have learnt in this activity. Make sure to record your results, and take careful note of any peculiarities that you come across as you work through the list.
- When you have finished your classification, you might like to print out your table of results using menu item Tools | Results Editors | Observational Results | Display/Print/Save Text... from the main exercise window.

Question 7

Compare your classifications against the notes given at the end of the activity.

This part of the activity has been quite involved, but you now should be able to classify any main sequence star according to its spectral characteristics. If you are in contact with anyone else doing this activity you may also have found that there is a certain degree of subjectivity to the classification, but that differences of opinion should be relatively minor.

This would be a suitable point to take a break from this activity. (Again, if you have not done so, remember to save the file of your results using the menu item Tools | Results Editors | Observational Results | Save Data... from the main exercise window.)

Using the telescope simulator to obtain stellar spectra

Background

This part of the activity will introduce you to an important practical aspect of stellar spectrometry. You will investigate how the choice of telescope and the time spent collecting data affect the quality of the spectrum obtained. As you will see, the quality of the spectrum limits an astronomer's ability to assign a spectral classification.

The VIREO program provides a choice of three (simulated) telescopes. Large modern telescopes are extremely expensive resources. Many are constructed and managed by international collaborations. This severely limits the individual astronomer's access to telescopes and forces the astronomer to make best use of the instruments available.

A large proportion of a telescope time is usually devoted to obtaining spectra. A spectrometer is attached to the telescope. The starlight from the telescope is passed into the spectrometer via a narrow opening, or slit. Inside the spectrometer a diffraction grating spreads the starlight out according to its wavelength. This spectrum is detected across a row of electronic detectors. Each individual detector collects photons within a narrow range of wavelengths. These narrow ranges are called 'channels'.

The number of photons arriving in each channel per second will be small. This is because the stars are faint, and therefore few photons arrive at the telescope, and because only a small fraction of these photons will fall within any individual channel.

You will be working with a simulation of a photon-counting spectrometer, which simply counts the number of photons received in each channel during the observation period (the integration or exposure time). Unfortunately, photons in any channel arrive randomly. This is rather similar to a familiar problem with buses. The timetable may predict, say, six buses past a particular stop during a 30 minute period, but you might count only four, or perhaps seven. Just as the bus service irregularities cause problems for passengers, so the irregularities in the arrival times of photons cause problems for astronomers.

The difficulty is that each time we measure a particular star's spectrum for the same length of time, we will count different numbers of photons even in the same individual channel. This variability is termed 'noise'.

The noisiness of the data is assessed in terms of the 'signal-to-noise ratio' (often denoted ' S/N '). For a given telescope and measurement period this is essentially the number of signal photons (equivalent to the number of buses predicted from the timetable) divided by the typical variation in the number of photons received. A low signal-to-noise ratio, for instance less than 10, means that features in the spectrum are being obscured by noise. When S/N has a numerical value of one the noise is as large as the signal and any feature seen in the spectrum might in fact be wholly due to random noise. So a spectrum with $S/N = 1$ would be useless – we could not infer anything from it.

For any source, the signal-to-noise ratio can only be improved by increasing the number of photons that constitute the measurement.

- In observing a particular star, what are the two ways in which the number of photons within an individual channel of a spectrometer could be increased?

- ❑ Either the measurement could be made over a longer time interval or a telescope with a larger collecting area could be used.

Since the second option – that of using a larger telescope – is expensive, astronomers usually adopt a compromise between these two factors.

Astronomical telescopes are usually very large reflecting telescopes, and are rated by the size of their primary mirrors. A 1.0 metre telescope has a primary mirror 1.0 metre in diameter and this mirror is the photon collection surface. Attaching a spectrometer to a larger telescope is analogous to inserting a larger funnel to a rain gauge – you collect a lot more light (or rain water).

Using the CLEA stellar spectra exercise you will assess the signal-to-noise ratio obtained with three different telescopes. These are 0.4 m, 1.0 m and 4.0 m telescopes. The 4.0 m telescope may have a mirror bigger than the room you are working in! (Note that the observatory software sometimes refers to the 1.0 m telescope as 0.9 m.)

Part 3 Making observations with different telescopes

This part of the activity should take about 45 minutes.

If you are continuing directly from the classification activity above, close the Classify Spectra window by clicking the X at the top right corner. If you are starting this part of the activity from the main opening screen (after log-in) of the software package, then select File | Run Exercise | “Classification of Stellar Spectra”. You will now see the screen titled ‘VIREO Exercise – The Classification of Stellar Spectra’.

- Start the observation exercise by accessing a telescope. Select Telescopes | Optical | Access 0.4 Meter. A pop-up window will tell you when you have been given control of the telescope. Click OK.

You will now see a simulated telescope control panel, with a monitor that can show the view through the telescope. At present the telescope is not in use, and the control panel monitor shows the dome interior and shutter in the red lighting that is used to preserve night vision within the observatory.

- Click the Open switch to start the night’s work. Once the dome is open, click the button currently labelled ‘Off’ to access the telescope control panel. This will open another window. Spend a few moments enjoying the view through the telescope’s small finder telescope. Note the stars being carried through the field of view by the Earth’s rotation. Notice the celestial coordinates, right ascension and declination, with the right ascension changing because of the Earth’s rotation (see Section 1.2.1 of the *Observational activities* booklet). Check the date and time on the left-hand side of the window.
- To take control of the telescope click Tracking. This causes the telescope to very slowly rotate about an axis parallel to the Earth’s rotation axis, compensating for the Earth’s rotation. The stars now seem to stand still. This is necessary for you to be able to collect light from the star in your spectrometer.

You will first of all make measurements on a bright star in the Pleiades star cluster.

- The telescope can be pointed at a predefined position on the sky by selecting the menu item Slew | Set Coordinates...

- In the box that appears, enter the coordinates 'R.A. 3h 48m 21s' and declination '23° 25' 17"', check that the Epoch of Input Coordinates is set to J2000 and press OK. This will place the star HD 23753, one of the brightest in the cluster, near the centre of the field of view of the finder.
- Slide the View control from Finder to Telescope to switch the monitor from the finder to the 0.4 m telescope.

Your star will now be near a pair of red lines. These lines represent the sides of the slit entrance to the telescope's spectrometer. When the light is centred between the lines, starlight will pass through the slit into the spectrometer.

- Centre the star on the slit using the N, S, E, W buttons. The rate of motion can be adjusted using the Slew Rate control.
- To use the spectrometer, first make sure that Spectrometer is selected in the Instrument panel and then click Access. A new window opens to give a graphical display of the spectrum as it is being recorded. You will be able to watch the spectrum being recorded, although the spectrum will not 'grow' because the normalized spectrum is displayed.
- Click the Go button to start collecting data. The spectrometer is set to stop counting once the signal-to-noise ratio reaches a value of 1000. This is a high value of S/N and is more than sufficient for any analysis that you will carry out later in the activity. Often it is not possible to obtain this value of S/N when astronomers are observing faint objects.

For all the stars that you measure in this activity it is good practice to record your observations in a systematic way. So, for instance, for every star you should have a record of the following details in your notes.

the telescope used
 date and time of observation
 star name
 right ascension
 declination
 apparent magnitude of star
 integration time/s
 total photon count
 average photon count per channel
 signal-to-noise ratio

Question 8

For your observation of HD 23753 note all the details listed above (note that the VIREO catalogue number for this star is N2230-02207). Watch the spectrum that appears and describe how it changes before the program automatically stops.

The photon count information allows us to work out how many channels this spectrometer has. The total number of photons detected must be equal to the number of channels multiplied by the average number of photons per channel thus the number of channels is the total number of photons divided by the average number per channel. From this, we can see that the spectrometer has 600 channels.

You might want to try running this count again.

- Close the spectrometer window using File | Exit Spectrometer, or by clicking on the X in the corner of the window and then click on Access again to run the count again.
- Make sure that for every observation you take that you record all the observational details in your notes. Note that you should also save the spectrum for future reference by clicking File | Data | Save Spectrum.... Save this spectrum with the default name followed by the letter A (to distinguish the first observation of this star) and make sure that you note down the reference name along with the details of the observation. [Your first file will be stored as e.g. N2230-02207A.SSP]

We are now going to repeat the observation using a telescope that has a 1.0 m diameter mirror. Within the simulator this is sometimes called the '1.0 m telescope' and at other times the 'KPNO 0.9 m telescope' (KPNO stands for Kitt Peak National Observatory – a major facility in the United States). We shall refer to it throughout this activity as the '1.0 m telescope'.

- To access the 1.0 m telescope click Telescopes | Optical | Access 1.0 Meter. The controls of this telescope are identical to those on the 0.4 m telescope that you used earlier.
- Open the Dome, switch on the Tracking, and point the telescope to the same star, using the Slew | Set Coordinates feature, and obtain the spectrum.
- Record the details of this observation in your notes and save the spectrum as N2230-02207B.SSP.
- You should now access a 4.0 m telescope. As before you will need to request time and access the telescope using the Telescopes menu in the main window.

Again, the procedure for operating this telescope is the same as for the smaller telescopes that you have already used. When you have control of the telescope, return to the same star and obtain the spectrum. Save the spectrum as N2230-02207C.SSP.

- What do you notice about the integration time required to reach a signal-to-noise ratio of 1000 between these observations?
- The integration time is longest on the 0.4 m telescope, and gets progressively shorter as larger telescopes are used.

Question 9

- (a) If a 1.0 m telescope collects 1000 photons in one second, how many photons would you expect a 4.0 m telescope to collect?
 - (b) If a 4.0 m and a 1.0 m telescope are used to observe the same object, then the larger telescope will reach a specified value of S/N in a shorter time than the smaller telescope. What is the relationship between these integration times on the two telescopes? Are your expectations borne out by the integration times required to reach $S/N = 1000$ in the case of HD 23753?
 - (c) If you were an astronomer applying for telescope time to measure the spectra of 50 stars that are of similar apparent magnitude to HD 23753, which one of the three telescopes would you ask to use? (Think about the time taken per observation – not just the integration time.)
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- Next you will measure the spectrum of a fainter star. This has no common name so we will call it S2. Move the telescope to 3h 44m 56s, 24° 29' 30", and centre it in the monitor. The VIREO catalogue name for this star is N2230-00564.
- From the telescope control panel switch the monitor back to the Finder using the View slider. You will see that the star is too faint to be distinguishable in the small finder telescope.
- Switch back to the 4.0 m telescope view and finalize the positioning. Take a reading, but in this case stop when the S/N reaches 100 by clicking Stop Count. As usual, record the details of the observation in your notes. Save the spectrum.

Bearing in mind what you have seen so far, think about the following.

- What do notice about the way in which this spectrum builds up? How does it compare to the previous spectra that you have measured?
- The early measurements may scarcely look like a spectrum. The noise is greater, and takes much longer to damp down.

Although the signal-to-noise ratio continually increases, it increases quite slowly. This emphasizes the point that high signal-to-noise measurements for fainter stars may require a long integration time.

Part 4 Classifying your two spectra and working out distances

This part of the activity should take about 45 minutes.

In this part you will classify the stars that you observed in Part 3 of the activity. The absolute magnitudes of main sequence stars are known (see Table 1). Using the apparent magnitudes of these two stars (which you will have noted in your observations) you can calculate the distance of the Pleiades cluster. The technique of determining distance in this way is called spectroscopic parallax.

Table 1 Absolute visual magnitude versus spectral type (from C.W. Allen, *Astrophysical Quantities*, The Athlone Press, London, 1973).

Spectral type	Absolute magnitude, M_V
O5	-5.8
B0	-4.1
B5	-1.1
A0	0.7
A5	2
F0	2.6
F5	3.4
G0	4.4
G5	5.1
K0	5.9
K5	7.3
M0	9
M5	11.8
M8	16

The first step is to classify the two stars.

- Switch back to using the spectral classification part of the software package.

- From the main window select the menu item Tools | Spectral Classification.
- Once you have the Classify Spectra window open you need to load the spectra that you took at the telescope. Select the menu item File | Unknown Spectra| Saved Spectra.

This will open a list of all your saved spectra. The filenames have the following format,

FILENAME . SSP

- Select the spectrum of HD 23753 taken with the 4m telescope, which will be called N2230-02207C.

Now use the Atlas of main sequence spectra to identify this spectrum as you did for the unknown spectra earlier. When you have classified this spectrum, repeat your analysis for the star S2

Question 10

- What are the spectral classes of HD 23753 and S2?
 - From Table 1, what are the absolute magnitudes of these two stars? (If the absolute magnitude of the spectral class is not listed in Table 1 then you should consider how to make a reasonable estimate given the tabulated data.)
-

The relationship that links absolute magnitude M , apparent magnitude m and distance d is

$$M = m - 5 \log(d/\text{pc}) + 5$$

(*An Introduction to the Sun and Stars*, Equation 3.16)

This can be rearranged to obtain an equation for the distance

$$d/\text{pc} = 10^{0.2(m-M+5)} \quad (1)$$

You may recall that absolute magnitude is equal to the apparent magnitude that the star would have if it was at a distance of 10 pc from Earth.

Now let us calculate the distance to HD 23753. The apparent magnitude is $m = 5.44$. The absolute magnitude (see the answer to Question 10) is -0.74 . Substituting these values in to Equation 1, gives

$$d/\text{pc} = 10^{0.2(5.44 - (-0.74) + 5)} = 10^{2.236} = 172 \text{ pc}$$

So the technique of spectroscopic parallax yields a distance to HD 23753 of 172 pc.

Question 11

Using the absolute magnitude that you determined in Question 10 and the apparent magnitude that you measured, calculate the distance to S2. Compare this result to that obtained for HD 23753.

As you found in your answer to Question 11 there is a wide variation between individual measurements of distance made using this technique. You can see from Table 1 that a difference in assigned spectral type of just one or two subclasses can cause a change in absolute magnitude of half a magnitude or more, which results in relatively large uncertainties in the distances calculated using spectroscopic parallax technique. In fact, if you had been unlucky it is possible

that one (or both!) stars may not have been members of the Pleiades at all, but stars which lie either in front of or behind the cluster. One way of overcoming these problems, at least as far as determining the distance to the Pleiades is concerned, is to make measurements of several stars and then to find their mean (or average) distance. This is the final task of the activity.

Question 12

Table 2 gives the coordinates of six stars in the Pleiades. You have already measured the distance to two of these stars. Using the technique of spectroscopic parallax, measure the distance to the remaining four stars. Hence estimate the distance to the Pleiades by calculating the mean distance to all six stars.

Table 2 The coordinates of the six target stars in the Pleiades.

Star name	VIREO catalogue name	Right ascension (J2000)	Declination
HD 23753	N2230-02207	3h 48m 21s	23° 25' 17"
S2	N2230-00564	3h 44m 56s	24° 29' 30"
HD 23733	N2230-01546	3h 48m 14s	24° 19' 06 "
S4	N2230-00974	3h 45m 35s	24° 05' 00"
S5	N2230-00863	3h 49m 39s	24° 13' 38"
HD 23713	N2230-01632	3h 48m 07s	24° 08' 32"

Endnote

In this activity you have studied main sequence stellar spectra and learnt to use the Harvard Spectral Classification scheme. You have also noticed the effects of noise on measurements, and tested the options of extending observation time or moving to a larger telescope to improve the signal-to-noise ratio. Finally you have used the telescope simulator to find a distance to the Pleiades cluster using the technique of spectroscopic parallax.

Answers to questions

Question 1

From your analysis of the spectrum of HD 124320 you should have found:

- The normalized intensities are 0.97 at 4050 Å and 0.76 at 4400 Å, so that the longer wavelength has about three-quarters of the intensity of the shorter wavelength.
- The continuum seems to have a maximum value at around 4040 Å, although this is not very clear because of the deep and wide spectral lines in this region.
- The fact that the continuum seems to peak at around 4000 Å and decreases at longer wavelengths implies that the spectral flux density has a maximum in the violet or blue part of the spectrum, and suggests the star will appear blue.

- (d) The blue colour would be indicative of a photosphere that is hotter than that of the Sun.

Question 2

The strength of spectral lines varies through the sequence of spectral classes because the strength of lines varies with photospheric temperature. This dependence arises because the number of atoms (or ions) that are in the particular electronic state that can give rise to a line is strongly dependent on temperature. For instance, the $H\gamma$ line arises when a photon is absorbed by a hydrogen atom in the $n = 2$ state. At low temperatures hydrogen is predominantly in the ground state ($n = 1$), and so the $H\gamma$ line will be weak. At high temperatures hydrogen will be excited to above the $n = 2$ state or may be ionized, and again the $H\gamma$ line will be weak. At intermediate temperatures there will be relatively large numbers of hydrogen atoms in the $n = 2$ state and the $H\gamma$ line will be strong.

Question 3

Using the Show Difference function, A1 is now easily the closest, with A5 quite close. So we can say that HD 124320 is between A1 and A5, and closer to A1, so class A2 is appropriate.

Question 4

The wavelength is approximately 3935 Å and its value is 0.14. This small peak in the difference indicates that the absorption line here is deeper in HD 124320 than in the reference. From the table, the standard wavelength of the CaII K line is 3933.68 Å. The 'II' means the calcium atoms producing the line are singly ionized. They are each missing one electron, because of the high temperature of their environment. (Note that the calcium II spectrum has two close lines at the visible/UV border. The other, the CaII H line, is at 3968 Å.)

Question 5

The CaII K line is visible throughout almost the entire range of reference spectra provided. The K line is rather shallow in O5, B0 and B6 (the hottest stars), and is hard to detect in M0 and M5 (the coolest stars). Figure 3.23 of Chapter 3 shows that the line strengths of ionized calcium drop off in both early and late spectral types, which corresponds with our findings.

Question 6

- (a) The spectrum appears to be midway between B0 and B6, and so a choice of spectral type of B3 would be appropriate. Making a classification to the nearest tenth of a class is quite difficult using a limited selection of reference spectra, so it would be hard to rule out the possibility that the star is class B2 or B4. So if you decided that HD 37767 is class B2, B3 or B4, then you would be in agreement with most astronomers. In fact, the Henry Draper catalogue classifies it as a type B3 star.
- (b) In your inspection of the spectrum of HD 37767 you should have found many of the lines listed in Table 3. Note that the measured wavelength column shows typical results – don't be concerned if your measurements differ by up to an ångström or so.

Table 3 Lines observed in the spectrum of HD 37767.

Measured wavelength/Å	Identification
3969.2	CaII (H line) – 3968.49 Å or HI (Hε) – 3970.07 Å.
4008.2	unknown
4025.3	HeI – 4026.19 Å
4100.9	HeII – 4100.04 or HI (Hδ) – 4101.75
4143.6	FeI – 4143.88
4340.0	HI (Hγ) – 4340.48
4387.2	HeI – 4387.93
4470.9	HeI – 4471.38

Notice that one line is unidentified, suggesting that it is not common enough to merit inclusion in the software's files. Every star is an individual, and spectral classification is about grouping similar, but not identical, stars.

There are also some ambiguous identifications. The line at 3969.2 Å may be the CaII H line or Hε. In fact, because the CaII K line is very weak in this spectrum and both the CaII H and K lines tend to occur with similar strengths, it is actually much more likely to be Hε. The line at 4100.9 Å is actually the Hδ line rather than the HeII line.

Question 7

The classifications of the stars HD 6111 and HD 5351 are described in detail below. A full reference list of all stars in the Unknown spectrum list is given in Table 4. In general, you should be able to classify most of these stars to within two-tenths of the spectral class listed here (i.e. a spectral class subdivision that is ± 2 from the tabulated value). Note that HD 35215 is classed as a B1.5 – you should be satisfied if you obtained B1 or B2. The one star that might cause you problems is SAO 81292 – this has the spectrum of an M4 or M5 star (in fact it is between these two) but shows emission lines that are not seen in any of the reference spectra. These peculiar emission features are denoted in the classification scheme by the letter 'e'.

Table 4 The spectral classes of the stars in the Unknown spectrum list.

Star	Class	Star	Class	Star	Class
HD 124320	A2	BD+63 137	M1	HD 242936	O8
HD 37767	B3	HD 66171	G2	HD 5351	K4
HD 35619	O7	HZ 948	F3	SAO 81292	M4.5e
HD 23733	A9	HD 35215	B1.5	HD 27685	G7
O 1015	B8	Feige 40	B4	HD 21619	A6
HD 24189	F6	Feige 41	A1	HD 23511	F4
HD 107399	F9	HD 6111	F8	HD 158659	B0
HD 240344	B4	HD 23863	A7		
HD 17647	G1	HD 221741	A3		

HD 6111

The classes F5, G0 and G6 all look very similar to the spectrum of HD 6111. The most prominent lines are the strong CaII (K and H) lines. There are three weaker lines: HeII, HI ($H\gamma$) and the CH/metals band. Look closely at the difference display for each of these. The G0 differences for these lines are all very close to zero, so G0 is the closest reference class for HD 6111. In fact, The catalogue lists the star as F8. This is quite similar to our own Sun. You might like to switch to the greyscale display and compare this to the solar spectrum in Figure 1.28 of *An Introduction to the Sun and Stars*.

HD 5351

For HD 5351, K5, M0 and M5 are all close. By studying the difference displays for each of the prominent lines, the CaI line at 4226.74 Å seems quite sensitive. You can also assess the CaII H and K lines, and the MnI line at 4030.70 Å. The catalogue classification is K4, though you might think it could reasonably be placed a few tenths later.

Question 8

You should have a table of observational details that resembles that given in Table 5. (There will be small differences in measured quantities between your results and those quoted here because of observational uncertainties.)

Table 5 Details of a single observation (see Question 8).

telescope	0.4 m
date and time	22/09/02 14:30
star	HD 23753
right ascension (J2000)	3h 48m 21s
Declination (J2000)	23° 25' 17"
apparent visual magnitude	5.44
integration time/s	102.5
total photon count	600 043 253
average photon count per channel	1000 073
signal-to-noise ratio	1000

As the spectrum was being measured you should have noticed that the individual data points jitter up and down. The ‘jitteriness’ is the noise, due to random arrival times of the photons. As you watch, the variations slowly die down. This means that in the course of the measurement the signal-to-noise ratio has improved (increased), which you may have noticed by watching the spectrometer signal-to-noise readout. A longer measurement time reduces the noise, giving a more reliable spectrum. ‘Integration’ is simply the time taken for the measurement.

Question 9

- (a) The number of photons collected will depend on the collecting area. The ratio of primary mirror diameters is 4 : 1 so the ratio of areas is $4^2 : 1^2$ or 16 : 1. The larger telescope will collect 16 times more photons, giving 16 000 photons in one second.
- (b) Since the same total number of photons is required for the given S/N , the larger telescope reaches the required level 16 times faster.

- (c) The sensible rule of thumb for applying for telescope time is to apply for the smallest diameter telescope that can be practicably used. We've already seen that the 0.4 m telescope can be used to measure the spectra of these stars, so clearly it looks as though it could be appropriate. However, let us work out how much observing time is needed on the 0.4 and 1.0 m telescopes to carry out all 50 observations.

The 0.4 m telescope requires an integration time of about 20 seconds per star, and the total integration time for the observations would be about 1000 seconds or about 17 minutes. On the 1.0 m telescope the integration time is about 3 seconds per star, or roughly about 3 minutes in total. However, the observation time includes time taken to move a telescope – as you have seen it would probably take at least a minute to change the pointing of the telescope from one star to another, so positioning any telescope would take 50 minutes. So on a 0.4 m telescope your observations would take 67 minutes, whereas on a 1.0 m telescope the observations would take 53 minutes. So, in this case there is no great advantage in using a larger telescope – the 0.4 m telescope would be sufficient – and an application to use the 1.0 m telescope is likely to be soundly rejected!

Question 10

- (a) The spectral class of HD 23753 appears to be almost identical to the reference spectrum B6, and is therefore classed as B6. Star S2 is very similar to spectral type M0 but not identical. Comparison with the K5 and M5 spectra indicates that it may be slightly closer to K5 so a spectral type of K9 is assigned.
- (b) HD 23753 has been assigned a spectral type of B6. The absolute magnitude of a type B6 star is not listed, but presumably lies between that of B5 ($M = -1.1$) and A0 ($M = 0.7$). An estimate of the absolute magnitude can be made in the following way. Spectral type B6 is 1 spectral subdivision beyond B5, and A0 is 5 spectral subdivisions beyond B5, and so the absolute magnitude of B6 could be estimated by taking the absolute magnitude of B5 and adding 1/5 of the difference between the absolute magnitudes of B5 and A0.

$$M(B6) = M(B5) + 1/5 \times (M(A0) - M(B5))$$

$$M(B6) = -1.1 + 1/5 \times (0.7 - (-1.1)) = -1.1 + 0.36 = -0.74$$

So, an estimate of the absolute magnitude of a B6 main sequence star is $M = -0.74$. (In fact, this only provides a crude estimate of the absolute magnitude, but one that is adequate for this calculation.)

Star S2 has been assigned a spectral type of K9. Again a rough estimate of absolute magnitude can be made in a similar way as was done for a type B6 star,

$$M(K9) = M(K5) + 4/5 \times (M(M0) - M(K5))$$

Using the values from Table 1,

$$M(K9) = 7.3 + 4/5 \times (9 - 7.3) = 8.66$$

So, an estimate of the absolute magnitude of a main sequence star of type K9 is $M = 8.66$.

Question 11

The distance to star S2 is found using values for apparent magnitude of $m = 14.25$ and absolute magnitude (see the answer to Question 10) of 8.66. Substituting these values in to Equation 1, gives

$$d/\text{pc} = 10^{0.2(14.25-8.66)+5} = 10^{2.118} = 131 \text{ pc}$$

So the technique of spectroscopic parallax yields a distance to star S2 of 131 pc.

This is quite different to the distance derived for HD 23753 (172 pc). The two stars do lie within the same cluster. Unfortunately, when 10 is raised to a power of a number, a small uncertainty in that number translates into a large uncertainty in the result. So minor uncertainties in the absolute or apparent magnitudes can lead to large uncertainties in distances.

Question 12

The results of the distance estimates to all six stars are shown in Table 6. Note that your results should be similar, but may not be identical to those shown here.

The mean distance of these stars is 130 pc, which agrees well with the currently accepted distance to the Pleiades of about 135pc.

Table 6 Results for the distance measurements for stars in the Pleiades.

Star name	Spectral type	M	m	$M - m$	distance/pc
HD 23753	B6	-0.74	5.44	6.18	172
S2	K9	8.66	14.25	5.59	131
HD 23733	F0	2.60	8.27	5.67	136
S4	G3	4.82	10.11	5.29	114
S5	K2	6.46	11.20	4.74	89
HD 23713	F6	3.60	9.25	5.65	135

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